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Constraint Identification and Algorithm Stabilization for Degenerate Nonlinear Programs

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Abstract. In the vicinity of a solution of a nonlinear programming problem at which both strict complementarity and linear independence of the active constraints may fail to hold, we describe a technique for distinguishing weakly active from strongly active constraints. We show that this information can be used to modify the sequential quadratic programming algorithm so that it exhibits superlinear convergence to the solution under assumptions weaker than those made in previous analyses.

Key words. Nonlinear Programming Problems, Degeneracy, Active Constrint Identification, Sequential Quadratic Programming

1. Introduction

Consider the following nonlinear programming problem with inequality constraints:

$$\text{NLP:} \qquad \min_z \phi(z) \qquad \text{subject to } g(z) \le 0, \tag{1}$$

where $\phi : \mathsf{R}^n \to \mathsf{R}$ and $g : \mathsf{R}^n \to \mathsf{R}^m$ are twice Lipschitz continuously differentiable functions. Optimality conditions for (1) can be derived from the Lagrangian for (1), which is

$$\mathcal{L}(z, \lambda) = \phi(z) + \lambda^T g(z), \tag{2}$$

where $\lambda \in \mathsf{R}^m$ is the vector of Lagrange multipliers. When a constraint qualification holds at z^* (see discussion below), the first-order necessary conditions for z^* to be a local solution of (1) are that there exists a vector $\lambda^* \in \mathsf{R}^m$ such that

$$\mathcal{L}_z(z^*, \lambda^*) = 0, \quad g(z^*) \le 0, \quad \lambda^* \ge 0, \quad (\lambda^*)^T g(z^*) = 0. \tag{3}$$

These relations are the well-known Karush-Kuhn-Tucker (KKT) conditions. The set $\mathcal{B}$ of active constraints at z^* is

$$\mathcal{B} = \{i = 1, 2, \ldots, m \,|\, g_i(z^*) = 0\}. \tag{4}$$

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It follows immediately from (3) that we can have $\lambda_i^* > 0$ only if $i \in \mathcal{B}$. The *weakly active* constraints are identified by the indices $i \in \mathcal{B}$ for which $\lambda_i^* = 0$ for all λ^* satisfying (3). Conversely, the *strongly active* constraints are those for which $\lambda_i^* > 0$ for at least one multiplier λ^* satisfying (3). The strict complementarity condition holds at z^* if there are no weakly active constraints.

We are interested in degenerate problems, those for which the active constraint gradients at the solution is linearly dependent or the strict complementarity condition fails to hold (or both). The first part of our paper describes a technique for partitioning $\mathcal{B}$ into weakly active and strongly active indices. Section 3 builds on the technique described by Facchinei, Fischer, and Kanzow [5] for identifying $\mathcal{B}$. Our technique requires the solution of a sequence of closely related linear programming subproblems in which the set of strongly active indices is assembled progressively. Solution of one additional linear program yields a Lagrange multiplier estimate λ such that the components λ_i for all strongly active indices i are bounded below by a positive constant.

In the second part of the paper, we use the cited technique to adjust the Lagrange multiplier estimate between iterations of the stabilized sequential quadratic programming (sSQP) algorithm described by Wright [18] and Hager [8]. The resulting technique has the advantage that it converges superlinearly under weaker conditions than considered in these earlier papers. We can drop the assumption of strict complementarity and a "sufficiently interior" starting point made in [18], and we do not need the stronger second-order conditions of [8]. Motivation for the sSQP approach came from work on primal-dual interior-point algorithms described in [19,12]. It is also closely related to the method of multipliers and the "recursive successive quadratic programming" approach of Bartholomew-Biggs [2]. (See Wright [16, Section 6] for a discussion of the similarities.)

Other work on stabilization of the SQP approach to yield superlinear convergence under weakened conditions has been performed by Fischer [6] and Wright [16]. Fischer proposed an algorithm in which an additional quadratic program is solved between iterations of SQP in order to adjust the Lagrange multiplier estimate. He proved superlinear convergence under conditions that are weaker than the standard assumptions but stronger than the ones made in this paper. Wright described superlinear local convergence properties of a class of inexact SQP methods and showed that sSQP and Fischer's method could be expressed as members of this class. This paper also introduced a modification of standard SQP that enforced only a subset of the linearized constraints—those in a "strictly active working set"—and permitted slight violations of the nonenforced constraints yet achieved superlinear convergence under weaker-than-usual conditions.

Bonnans [3] showed that when strict complementarity fails to hold but the active constraint gradients are linearly independent, then the standard SQP algorithm (in which any nonuniqueness in the solution of the SQP subproblem is resolved by taking the solution of minimum norm) converges superlinearly.

Our concern here is with *local* behavior, so we assume availability of a starting point (z^0, λ^0) that is "sufficiently close" to the optimal primal-dual set. We believe, however, that ingredients of the approach proposed here can be embed-

ded in practical algorithms, such as SQP algorithms that include modifications (merit functions and filters) to ensure global convergence. We believe also that this approach could be used to enhance the robustness and convergence rate of other types of algorithms, including augmented Lagrangian and interior-point algorithms, in problems in which there is degeneracy at the solution. We mention one such extension in Section 6.

2. Assumptions, Notation, and Basic Results

We now review the optimality conditions for (1) and outline the assumptions that are used in subsequent sections. These include the second-order sufficient condition we use here, the Mangasarian-Fromovitz constraint qualification, and the definition of weakly-active indices.

Recall the KKT conditions (3). The set of "optimal" Lagrange multipliers λ^* is denoted by $\mathcal{S}_\lambda$, and the primal-dual optimal set is denoted by $\mathcal{S}$. Specifically, we have

$$\mathcal{S}_\lambda = \{\lambda^* \,|\, \lambda^* \text{ satisfies (3)}\}, \quad \mathcal{S} = \{z^*\} \times \mathcal{S}_\lambda. \tag{5}$$

An alternative, compact form of the KKT conditions is the following variational inequality formulation:

$$\begin{bmatrix} \nabla\phi(z^*) + \nabla g(z^*)\lambda^* \\ g(z^*) \end{bmatrix} \in \begin{bmatrix} 0 \\ N(\lambda^*) \end{bmatrix}, \tag{6}$$

where $N(\lambda)$ is the set defined by

$$N(\lambda) \stackrel{\text{def}}{=} \begin{cases} \{y \,|\, y \le 0 \text{ and } y^T\lambda = 0\} & \text{if } \lambda \ge 0, \\ \emptyset & \text{otherwise.} \end{cases} \tag{7}$$

We now introduce notation for subsets of the set $\mathcal{B}$ of active constraint indices at z^*, defined in (4). For any optimal multiplier $\lambda^* \in \mathcal{S}_\lambda$, we define the set $\mathcal{B}_+(\lambda^*)$ to be the "support" of λ^*, that is,

$$\mathcal{B}_+(\lambda^*) = \{i \in \mathcal{B} \,|\; \lambda_i^* > 0\}.$$

We define $\mathcal{B}_+$ (without argument) as

$$\mathcal{B}_+ \stackrel{\text{def}}{=} \cup_{\lambda^* \in \mathcal{S}_\lambda} \mathcal{B}_+(\lambda^*); \tag{8}$$

this set contains the indices of the *strongly active* constraints. Its complement in $\mathcal{B}$ is denoted by $\mathcal{B}_0$, that is,

$$\mathcal{B}_0 \stackrel{\text{def}}{=} \mathcal{B} \backslash \mathcal{B}_+.$$

This set $\mathcal{B}_0$ contains the *weakly active* constraint indices, those indices $i \in \mathcal{B}$ such that $\lambda_i^* = 0$ for all $\lambda^* \in \mathcal{S}_\lambda$. In later sections, we make use of the quantity ϵ_λ defined by

$$\epsilon_\lambda \stackrel{\text{def}}{=} \max_{\lambda^* \in \mathcal{S}_\lambda} \min_{i \in \mathcal{B}_+} \lambda_i^*. \tag{9}$$

Note by the definition of $\mathcal{B}_+$ that $\epsilon_\lambda > 0$.

The Mangasarian-Fromovitz constraint qualification (MFCQ) [11] holds at z^* if there is a vector $\bar{y} \in \mathsf{R}^n$ such that

$$\nabla g_i(z^*)^T \bar{y} < 0 \quad \text{for all } i \in \mathcal{B}.$$

By defining $\nabla g_{\mathcal{B}}$ to be the $n \times |\mathcal{B}|$ matrix whose rows are $\nabla g_i(\cdot)$, $i \in \mathcal{B}$, we can write this condition alternatively as

$$\nabla g_{\mathcal{B}}(z^*)^T \bar{y} < 0. \tag{10}$$

It is well known that MFCQ is equivalent to boundedness of the set $\mathcal{S}_\lambda$; see Gauvin [7].

Since $\mathcal{S}_\lambda$ is defined by the linear conditions $\nabla \phi(z^*) + \nabla g(z^*)\lambda^*$ and $\lambda^* \geq 0$, it is closed and convex. Therefore, under MFCQ, it is also compact.

We assume throughout that the following second-order condition is satisfied: there is $\sigma > 0$ such that

$$w^T \mathcal{L}_{zz}(z^*, \lambda^*) w \geq \sigma \|w\|^2, \quad \text{for all } \lambda^* \in \mathcal{S}_\lambda, \tag{11}$$

and for all w such that

$$\begin{aligned} &\nabla g_i(z^*)^T w = 0, \text{ for all } i \in \mathcal{B}_+, \\ &\nabla g_i(z^*)^T w \leq 0, \text{ for all } i \in \mathcal{B}_0. \end{aligned} \tag{12}$$

This condition is referred to as Condition 2s.1 in [16, Section 3]. Weaker second-order conditions, stated in terms of a quadratic growth condition of the objective $\phi(z)$ in a feasible neighborhood of z^*, are discussed by Bonnans and Ioffe [4] and Anitescu [1].

Our standing assumption for this paper is as follows.

Assumption 1. *The first-order conditions (3), the MFCQ (10), and the second-order condition (11), (12) are satisfied at z^*. Moreover, the functions ϕ and g are twice Lipschitz continuously differentiable in a neighborhood of z^*.*

The following is an immediate consequence of this assumption.

Theorem 1. *Suppose that Assumption 1 holds. Then z^* is an isolated stationary point and a strict local minimizer of (1).*

Proof. See Robinson [13, Theorems 2.2 and 2.4].

We use the notation $\delta(\cdot)$ to denote distances from the primal, dual, and primal-dual optimal sets, according to context. Specifically, we define

$$\delta(z) \stackrel{\text{def}}{=} \|z - z^*\|, \quad \delta(\lambda) \stackrel{\text{def}}{=} \operatorname{dist}(\lambda, \mathcal{S}_\lambda), \quad \delta(z, \lambda) \stackrel{\text{def}}{=} \operatorname{dist}((z, \lambda), \mathcal{S}), \tag{13}$$

where $\|\cdot\|$ denotes the Euclidean norm unless a subscript specifically indicates otherwise. We also use $P(\lambda)$ to denote the projection of λ onto $\mathcal{S}_\lambda$; that is, we

have $P(\lambda) \in \mathcal{S}_\lambda$ and $\|P(\lambda) - \lambda\| = \mathrm{dist}\,(\lambda, \mathcal{S}_\lambda)$. Note that from (13) we have $\delta(z)^2 + \delta(\lambda)^2 = \delta(z,\lambda)^2$, and therefore

$$\delta(z) \le \delta(z,\lambda), \qquad \delta(\lambda) \le \delta(z,\lambda). \tag{14}$$

Using Assumption 1, we can prove the following result, which gives a practical way to estimate the distance $\delta(z,\lambda)$ of (z,λ) to the primal-dual solution set $\mathcal{S}$.

Theorem 2. *Suppose that Assumption 1 holds. Then there are positive constants δ, κ_0, and κ_1 such that for all (z,λ) with $\delta(z,\lambda) \le \delta$, the quantity $\eta(z,\lambda)$ defined by*

$$\eta(z,\lambda) \stackrel{\mathrm{def}}{=} \left\| \begin{bmatrix} \mathcal{L}_z(z,\lambda) \\ \min(\lambda, -g(z)) \end{bmatrix} \right\| \tag{15}$$

(where $\min(\lambda, -g(z))$ denotes the vector whose ith component is $\min(\lambda_i, -g_i(z))$) satisfies

$$\kappa_0 \delta(z,\lambda) \le \eta(z,\lambda) \le \kappa_1 \delta(z,\lambda).$$

See Facchinei, Fischer, and Kanzow [5, Theorem 3.6], Wright [16, Theorem A.1], and Hager and Gowda [9, Lemma 2] for proofs of this result. (The second-order condition is stated in a slightly different fashion in [5] but is equivalent to (11), (12).)

We use order notation in the following (fairly standard) way: If two matrix, vector, or scalar quantities M and A are functions of a common quantity, we write $M = O(\|A\|)$ if there is a constant β such that $\|M\| \le \beta\|A\|$ whenever $\|A\|$ is sufficiently small. We write $M = \Omega(\|A\|)$ if there is a constant β such that $\|M\| \ge \beta^{-1}\|A\|$ whenever $\|A\|$ sufficiently small, and $M = \Theta(\|A\|)$ if both $M = O(\|A\|)$ and $M = \Omega(\|A\|)$. We write $M = o(\|A\|)$ if for all sequences $\{A_k\}$ with $\|A_k\| \to 0$, the corresponding sequence $\{M_k\}$ satisfies $\|M_k\|/\|A_k\| \to 0$. By using this notation, we can rewrite the conclusion of Theorem 2 as follows:

$$\eta(z,\lambda) = \Theta(\delta(z,\lambda)). \tag{16}$$

3. Detecting Active Constraints

We now describe a procedure, named Procedure ID0, for identifying those inequality constraints that are active and the solution, and classifying them according to whether they are weakly active or strongly active. We prove that Procedure ID0 classifies the indices correctly given a point (z,λ) sufficiently close to the primal-dual optimal set $\mathcal{S}$. Finally, we describe some implementation issues for this procedure.

3.1. The Detection Procedure

Facchinei, Fischer, and Kanzow [5] showed that the function $\eta(z,\lambda)$ defined in (16) can be used as the basis of a scheme for identifying the active set $\mathcal{B}$. Choosing some $\tau \in (0,1)$, they estimated

$$\mathcal{A}(z,\lambda) \stackrel{\text{def}}{=} \{i = 1,2,\dots,m \mid g_i(z) \geq -\eta(z,\lambda)^\tau\}. \tag{17}$$

We have the following result.

Theorem 3. *Suppose that Assumption 1 holds. Then there exists $\delta > 0$ such that for all (z,λ) with $\delta(z,\lambda) \leq \delta$, we have $\mathcal{A}(z,\lambda) = \mathcal{B}$.*

Proof. The result follows immediately from [5, Definition 2.1, Theorem 2.3] and Theorem 2 above.

A scheme for estimating $\mathcal{B}_+$ (hence, $\mathcal{B}_0$) is described in [5], but it requires the strict MFCQ condition to hold, which implies that $\mathcal{S}_\lambda$ is a singleton. Here we describe a more complicated scheme for estimating $\mathcal{B}_+$ that requires only the conditions of Theorem 3 to hold.

Our scheme is based on linear programming subproblems of the following form, for a given parameter $\tau \in (0,1)$ and a given set $\hat{\mathcal{A}} \subset \mathcal{A}(z,\lambda)$:

$$\max_{\tilde{\lambda}} \textstyle\sum_{i \in \hat{\mathcal{A}}} \tilde{\lambda}_i \ \text{ subject to} \tag{18a}$$

$$-\eta(z,\lambda)^\tau \leq \nabla\phi(z) + \textstyle\sum_{i \in \mathcal{A}(z,\lambda)} \tilde{\lambda}_i \nabla g_i(z) \leq \eta(z,\lambda)^\tau \tag{18b}$$

$$\tilde{\lambda}_i \geq 0, \ \text{ for all } i \in \mathcal{A}(z,\lambda); \quad \tilde{\lambda}_i = 0 \ \text{ otherwise.} \tag{18c}$$

Note that the objective function involves elements $\tilde{\lambda}_i$ only for indices i in the subset $\hat{\mathcal{A}}$, whereas the $\tilde{\lambda}_i$ are permitted to be nonzero for all $i \in \mathcal{A}(z,\lambda)$. The idea is that $\hat{\mathcal{A}}$ contains those indices that *may* belong to $\mathcal{B}_0$; by the time we solve (18), we have already decided that the other indices $i \in \mathcal{A}(z,\lambda) \backslash \hat{\mathcal{A}}$ probably belong to $\mathcal{B}_+$.

The complete procedure is as follows.

Procedure ID0
Given constants τ and $\hat{\tau}$ satisfying $0 < \hat{\tau} < \tau < 1$, and point (z,λ);
Evaluate $\eta(z,\lambda)$ from (15) and $\mathcal{A}(z,\lambda)$ from (17);
Define $\hat{\mathcal{A}}_{\text{init}} = \mathcal{A}(z,\lambda) \backslash \{i \mid \lambda_i \geq \eta(z,\lambda)^{\hat{\tau}}\}$;
$\hat{\mathcal{A}} \leftarrow \hat{\mathcal{A}}_{\text{init}}$;
repeat
  solve (18) to find $\tilde{\lambda}$;
  set $\mathcal{C} = \{i \in \hat{\mathcal{A}} \mid \tilde{\lambda}_i \geq \eta(z,\lambda)^{\hat{\tau}}\}$;
  if $\mathcal{C} = \emptyset$
    stop with $\mathcal{A}_0 = \hat{\mathcal{A}}$, $\mathcal{A}_+ = \mathcal{A}(z,\lambda) \backslash \hat{\mathcal{A}}$;
  else
    set $\hat{\mathcal{A}} \leftarrow \hat{\mathcal{A}} \backslash \mathcal{C}$;

if $\hat{\mathcal{A}} = \emptyset$
stop with $\mathcal{A}_0 = \emptyset$, $\mathcal{A}_+ = \mathcal{A}(z, \lambda)$;
end(if)
end(if)
end(repeat)

This procedure terminates finitely; in fact, the number of times the "repeat" loop executes is bounded by the cardinality of $\hat{\mathcal{A}}_{\text{init}}$.

We prove that Procedure ID0 successfully identifies $\mathcal{B}_+$ (for all $\delta(z, \lambda)$ sufficiently small) in several steps, culminating in Theorem 4. First, we estimate the distance of $(z, \tilde{\lambda})$ to the solution set $\mathcal{S}$, where $\tilde{\lambda}$ is the solution of (18) for some $\hat{\mathcal{A}}$.

Lemma 1. *Suppose that Assumption 1 holds. Then there are positive constants δ_0 and κ_2 such that whenever $\delta(z, \lambda) \leq \delta_0$, any feasible point $\tilde{\lambda}$ of (18) at any iteration of Procedure ID0 satisfies*

$$\delta(z, \tilde{\lambda}) \leq \kappa_2 \delta(z, \lambda)^{\tau}.$$

Proof. Initially choose $\delta_0 = \delta$ for δ defined in Theorem 3, so that $\mathcal{A}(z, \lambda) = \mathcal{B}$. Hence, we have $\hat{\mathcal{A}} \subset \mathcal{B}$ at all iterations of Procedure ID0.

We now estimate $\eta(z, \tilde{\lambda})$ using the definition (15). We have directly from the constraints (18b) that

$$\|\mathcal{L}_z(z, \tilde{\lambda})\|_{\infty} \leq \eta(z, \lambda)^{\tau}.$$

For the vector $\min(\tilde{\lambda}, -g(z))$, we have for $i \in \mathcal{B}$ that $g_i(z^*) = 0$ and $\tilde{\lambda}_i \geq 0$, and so

$$i \in \mathcal{B} \;\Rightarrow\; |\min(\tilde{\lambda}_i, -g_i(z))| \leq |g_i(z)| = O(\|z - z^*\|) = O(\delta(z, \lambda)).$$

Meanwhile for $i \notin \mathcal{B} = \mathcal{A}(z, \lambda)$, we have $\tilde{\lambda}_i = 0$ and $g_i(z^*) < 0$, and so

$$i \notin \mathcal{B} \;\Rightarrow\; |\min(\tilde{\lambda}_i, -g_i(z))| = \max(0, g_i(z)) \leq |g_i(z) - g_i(z^*)| = O(\delta(z, \lambda)).$$

By substituting these estimates into (15), and using the equivalence of $\|\cdot\|_{\infty}$ and the Euclidean norm and the result of Theorem 2, we have that there is a constant $\bar{\kappa}_2 > 0$ such that

$$\eta(z, \tilde{\lambda}) \leq \bar{\kappa}_2 \delta(z, \lambda)^{\tau}.$$

Using Theorem 2 again, we have

$$\delta(z, \tilde{\lambda}) \leq \kappa_0^{-1} \eta(z, \tilde{\lambda}) \leq \kappa_0^{-1} \bar{\kappa}_2 \delta(z, \lambda)^{\tau}, \tag{19}$$

giving the result.

In the next two lemmas and Theorem 4, we show that for $\delta(z, \lambda)$ sufficiently small, Procedure ID0 terminates with $\mathcal{A}_0 = \mathcal{B}_0$ and $\mathcal{A}_+ = \mathcal{B}_+$.

Lemma 2. *Suppose that Assumption 1 holds. Then there is $\delta_1 > 0$ such that whenever $\delta(z, \lambda) \leq \delta_1$, Procedure ID0 terminates with $\mathcal{B}_0 \subset \mathcal{A}_0$.*

Proof. Since we know the procedure terminates finitely, we need show only that $\mathcal{B}_0 \subset \hat{\mathcal{A}}$ at all iterations of the procedure. Initially set $\delta_1 = \delta_0 \le \delta$, so that $\mathcal{A}(z,\lambda) = \mathcal{B}$ and the result of Lemma 1 holds. Suppose for contradiction there is an index $j \in \mathcal{B}_0$ such that j either is not included in the initial index set $\hat{\mathcal{A}}_{\rm init}$ or else is deleted from $\hat{\mathcal{A}}$ at some iteration of Procedure ID0.

Suppose first that j is not included in $\hat{\mathcal{A}}_{\rm init}$. Then we must have $\lambda_j > \eta(z,\lambda)^{\hat{\tau}}$, which by Theorem 2 implies that

$$\delta(z,\lambda) \ge |\lambda_j| \ge \eta(z,\lambda)^{\hat{\tau}} \ge \kappa_0^{\hat{\tau}} \delta(z,\lambda)^{\hat{\tau}}. \tag{20}$$

However, by decreasing δ_1 and using $\hat{\tau} \in (0,1)$, we can ensure that (20) does not hold whenever $\delta(z,\lambda) \le \delta_1$. Hence, j is included in $\hat{\mathcal{A}}_{\rm init}$.

Suppose now that $j \in \mathcal{B}_0$ is deleted from $\hat{\mathcal{A}}$ at some subsequent iteration. For this to happen, the subproblem (18) must have a solution $\tilde{\lambda}$ with

$$\tilde{\lambda}_j > \eta(z,\lambda)^{\hat{\tau}} \tag{21}$$

for some $\hat{\mathcal{A}} \subset \mathcal{B}$. Hence from Theorem 2, we have that

$$\delta(z,\tilde{\lambda}) \ge \tilde{\lambda}_j > \eta(z,\lambda)^{\hat{\tau}} \ge \kappa_0^{\hat{\tau}} \delta(z,\lambda)^{\hat{\tau}}. \tag{22}$$

By combining the result of Lemma 1 with (22), we have that

$$\kappa_2 \delta(z,\lambda)^{\tau} \ge \kappa_0^{\hat{\tau}} \delta(z,\lambda)^{\hat{\tau}}.$$

However, this inequality cannot hold when $\delta(z,\lambda)$ is smaller than $(\kappa_0^{\hat{\tau}}\kappa_2^{-1})^{1/(\tau-\hat{\tau})}$. Therefore, by decreasing δ_1 if necessary, we have a contradiction in this case also.

Lemma 3. *Suppose that Assumption 1 holds. Then there is $\delta_2 > 0$ such that whenever $\delta(z,\lambda) \le \delta_2$, Procedure ID0 terminates with $\mathcal{B}_+ \subset \mathcal{A}_+$.*

Proof. Given any $j \in \mathcal{B}_+$, we have for sufficiently small choice of δ_2 that $j \in \mathcal{A}(z,\lambda)$. We prove the result by showing that Procedure ID0 cannot terminate with $j \in \mathcal{A}_0$.

We initially set $\delta_2 = \delta_1$, where δ_1 is the constant from Lemma 2. (We reduce it as necessary, but maintain $\delta_2 > 0$, in the course of the proof.) For contradiction, assume that there is $j \in \mathcal{B}_+$ such that $j \in \hat{\mathcal{A}}$ at all iterations of Procedure ID0, including the iteration on which the procedure terminates and sets $\mathcal{A}_0 = \hat{\mathcal{A}}$. Recalling the definition (9) of ϵ_λ, we use compactness of $\mathcal{S}_\lambda$ to choose $\lambda^* \in \mathcal{S}_\lambda$ such that $\epsilon_\lambda = \min_{i \in \mathcal{B}_+} \lambda_i^*$. In particular, we have

$$\lambda_j^* \ge \epsilon_\lambda > 0$$

for our chosen index j. We claim that, by reducing δ_2 if necessary, we can ensure that λ^* is feasible for (18) whenever $\delta(z,\lambda) \le \delta_2$. Obviously, since $\mathcal{A}(z,\lambda) = \mathcal{B}$ by Theorem 3, λ^* is feasible with respect to (18c). Since $\lambda^* \in \mathcal{S}_\lambda$ and

$$\|z - z^*\| \le \delta(z,\lambda) \le \kappa_0^{-1} \eta(z,\lambda),$$

we have

$$\left\| \nabla\phi(z) + \sum_{i=1}^{m} \lambda_i^* \nabla g_i(z) \right\|_\infty = \left\| \nabla\phi(z) - \nabla\phi(z^*) + \sum_{i=1}^{m} \lambda_i^* (\nabla g_i(z) - \nabla g_i(z^*)) \right\|_\infty$$
$$\leq M\|z - z^*\| \leq M\kappa_0^{-1}\eta(z,\lambda), \tag{23}$$

for some constant M that depends on the norms of $\nabla^2\phi(\cdot)$ and $\nabla^2 g_i(\cdot)$, $i \in \mathcal{B}_+$ in the neighborhood of z^* and on a bound on the set $\mathcal{S}_\lambda$ (which *is* bounded, because of MFCQ). Since $\tau < 1$ and since $\eta(z,\lambda) = \Theta(\delta(z,\lambda))$, we can reduce δ_2 if necessary to ensure that

$$M\kappa_0^{-1}\eta(z,\lambda) < \eta(z,\lambda)^\tau$$

whenever $\delta(z,\lambda) \leq \delta_2$, thereby ensuring that the constraints (18b) are satisfied by λ^*.

Since λ^* is feasible for (18), a lower bound on the optimal objective is

$$\sum_{i\in\hat{\mathcal{A}}} \lambda_i^* \geq \lambda_j^* \geq \epsilon_\lambda.$$

However, since Procedure ID0 terminates with $j \in \hat{\mathcal{A}}$, we must have that $\mathcal{C} = \emptyset$ for the solution $\tilde{\lambda}$ of (18) with this particular choice of $\hat{\mathcal{A}}$. But we can have $\mathcal{C} = \emptyset$ only if $\tilde{\lambda}_i < \eta(z,\lambda)^{\hat{\tau}}$ for all $i \in \hat{\mathcal{A}}$, which means that the optimal objective is no greater than $m\eta(z,\lambda)^{\hat{\tau}}$. But since $\eta(z,\lambda) = \Theta(\delta(z,\lambda))$, we can reduce δ_2 if necessary to ensure that

$$m\eta(z,\lambda)^{\hat{\tau}} < \epsilon_\lambda$$

whenever $\delta(z,\lambda) \leq \delta_2$. This gives a contradiction, so that $\mathcal{A}_0$ (which is set by Procedure ID0 to the final $\hat{\mathcal{A}}$) can contain no indices $j \in \mathcal{B}_+$. Since $\mathcal{B}_+ \subset \mathcal{B} = \mathcal{A}(z,\lambda)$ whenever $\delta(z,\lambda) \leq \delta_2$, we must therefore have $\mathcal{B}_+ \subset \mathcal{A}_+$, as claimed.

By using the quantity δ_2 from Lemma 3, we combine this result with Theorem 3 and Lemma 2 to obtain the following theorem.

Theorem 4. *Suppose that Assumption 1 holds. Then there is $\delta_2 > 0$ such that whenever $\delta(z,\lambda) \leq \delta_2$, Procedure ID0 terminates with $\mathcal{A}_+ = \mathcal{B}_+$ and $\mathcal{A}_0 = \mathcal{B}_0$.*

3.2. Scheme for Finding an Interior Multiplier Estimate

We now describe a scheme for finding a vector $\hat{\lambda}$ that is close to $\mathcal{S}_\lambda$ but not too close to the relative boundary of this set. In other words, the quantity $\min_{i\in\mathcal{B}_+} \hat{\lambda}_i$ is not too far from its maximum achievable value ϵ_λ.

We find $\hat{\lambda}$ by solving a linear programming problem similar to (18) but containing an extra variable to represent $\min_{i\in\mathcal{B}_+} \hat{\lambda}_i$. We state this problem as

follows:

$$\max_{\hat{t},\hat{\lambda}} \hat{t} \text{ subject to} \tag{24a}$$

$$\hat{t} \le \hat{\lambda}_i, \text{ for all } i \in \mathcal{A}_+, \tag{24b}$$

$$-\eta(z,\lambda)^\tau e \le \nabla\phi(z) + \textstyle\sum_{i\in\mathcal{A}_+} \hat{\lambda}_i \nabla g_i(z) \le \eta(z,\lambda)^\tau e \tag{24c}$$

$$\hat{\lambda}_i \ge 0, \text{ for all } i \in \mathcal{A}_+; \quad \hat{\lambda}_i = 0 \text{ otherwise.} \tag{24d}$$

Theorem 5. *Suppose that Assumption 1 holds. Then there is a positive number δ_3 such that (24) is feasible and bounded whenever $\delta(z,\lambda) \le \delta_3$, and its optimal objective is at least ϵ_λ (for ϵ_λ defined in (9)). Moreover, there is a constant $\beta' > 0$ such that $\delta(z,\hat{\lambda}) \le \beta'\delta(z,\lambda)^\tau$.*

Proof. Let $\lambda^* \in \mathcal{S}_\lambda$ be chosen so that $\epsilon_\lambda = \min_{i\in\mathcal{B}_+} \lambda^*_i$. We show first that $(\hat{t},\hat{\lambda}) = (\epsilon_\lambda, \lambda^*)$ is feasible for (24), thereby proving that this linear program is feasible and that the optimum objective value is at least ϵ_λ.

Initially we set $\delta_3 = \delta_2$. By Definition (9), the constraint (24b) is satisfied by $(\hat{t},\hat{\lambda}) = (\epsilon_\lambda, \lambda^*)$. Since $\delta(z,\lambda) \le \delta_3 = \delta_2$, we have from Theorem 4 that $\mathcal{A}_+ = \mathcal{B}_+$, so that (24d) also holds. Satisfaction of (24c) follows from (23), by choice of δ_2. Moreover, it is clear from $\mathcal{A}_+ = \mathcal{B}_+$ that the optimal $(\hat{t},\hat{\lambda})$ will satisfy $\hat{t} = \min_{i\in\mathcal{B}_+} \hat{\lambda}_i$.

We now show that the problem (24) is bounded for $\delta(z,\lambda)$ sufficiently small. Let $\bar{y}$ be the vector in (10), and decrease δ_3 if necessary so that we can choose a number $\zeta > 0$ such that

$$\delta(z,\lambda) \le \delta_3 \;\;\Rightarrow\;\; \bar{y}^T \nabla g_i(z) \le -\zeta, \text{ for all } i \in \mathcal{A}_+ = \mathcal{B}_+. \tag{25}$$

From the constraints (24c) and the triangle inequality, we have that

$$\begin{aligned}
\left\| \sum_{i\in\mathcal{A}_+} \hat{\lambda}_i \bar{y}^T \nabla g_i(z) \right\|_1 &\le \|\bar{y}^T\nabla\phi(z)\|_1 + \left\| \bar{y}^T\nabla\phi(z) + \sum_{i\in\mathcal{A}_+} \hat{\lambda}_i \bar{y}^T \nabla g_i(z) \right\|_1 \\
&\le \|\bar{y}\|_1 \, \|\nabla\phi(z)\|_\infty + \|\bar{y}\|_1 \left\| \nabla\phi(z) + \sum_{i\in\mathcal{A}_+} \hat{\lambda}_i \nabla g_i(z) \right\|_\infty \\
&\le \|\bar{y}\|_1 \, \|\nabla\phi(z)\|_\infty + \|\bar{y}\|_1 \eta(z,\lambda)^\tau.
\end{aligned}$$

However, from (25) and $\hat{\lambda}_i \ge 0$, $i \in \mathcal{A}_+$, we have that

$$\left\| \sum_{i\in\mathcal{A}_+} \hat{\lambda}_i \bar{y}^T \nabla g_i(z) \right\|_1 \ge \left\| \hat{\lambda}_{\mathcal{A}_+} \right\|_1 \zeta.$$

By combining these bounds, we obtain that

$$\left\| \hat{\lambda}_{\mathcal{A}_+} \right\|_1 \le \zeta^{-1} \|\bar{y}\|_1 \left[\|\nabla\phi(z)\|_\infty + \eta(z,\lambda)^\tau \right],$$

whenever $\delta(z,\lambda) \le \delta_3$, so that the feasible region for (24) is bounded, as claimed.

To prove our final claim that $\delta(z,\hat{\lambda}) \le \beta' \delta(z,\lambda)^\tau$ for some $\beta' > 0$, we use Theorem 2. We have from (24c) and the cited theorem that

$$\left\| \mathcal{L}_z(z,\hat{\lambda}) \right\|_\infty \le \eta(z,\lambda)^\tau \le \kappa_1^\tau \delta(z,\lambda)^\tau.$$

For $i \in \mathcal{A}_+ = \mathcal{B}_+$, we have from $\hat{\lambda}_i \ge \epsilon_\lambda$ and $g_i(z^*) = 0$ that

$$\begin{aligned} i \in \mathcal{A}_+ \quad \Rightarrow \quad \left| \min(\hat{\lambda}_i, -g_i(z)) \right| &\le |g_i(z)| \le |g_i(z) - g_i(z^*)| \\ &= O(\|z - z^*\|) = O(\delta(z,\lambda)). \end{aligned}$$

For $i \notin \mathcal{A}_+$, we have $\hat{\lambda}_i = 0$ and $g_i(z^*) \le 0$, and so

$$\begin{aligned} i \notin \mathcal{A}_+ \quad \Rightarrow \quad \left| \min(\hat{\lambda}_i, -g_i(z)) \right| &= \max(0, g_i(z)) \le |g_i(z) - g_i(z^*)| \\ &= O(\|z - z^*\|) = O(\delta(z,\lambda)). \end{aligned}$$

By substituting the last three bounds into (15) and applying Theorem 2, we obtain the result.

3.3. Computational Aspects

Solution of the linear programs (18) is in general less expensive than solution of the quadratic programs or complementarity problems that must be solved at each step of an optimization algorithm with rapid local convergence. Linear programming software is easy to use and readily available. Moreover, given a point (z,λ) with $\delta(z,\lambda)$ small, we can expect $\hat{\mathcal{A}}_{\text{init}}$ not to contain many more indices than the weakly active set $\mathcal{B}_0$, so that few iterations of the "repeat" loop in Procedure ID0 should be needed.

Finally, we note that when more than one iteration of the "repeat" loop is needed in Procedure ID0, the linear programs to be solved at successive iterations differ only in the cost vector in (18a). Therefore, if the dual formulation of (18) is used, the solution of one linear program can typically be obtained at minimal cost from the solution of the previous linear program in the sequence. To clarify this claim, we simplify notation and write (18) as follows:

$$\max c^T \pi \quad \text{subject to } \; b_1 \le A\pi \le b_2, \;\; \pi \ge 0, \tag{26}$$

where $\pi = [\lambda_i]_{i \in \mathcal{A}(z,\lambda)}$, while c, b_1, b_2, and A are defined in obvious ways. In particular, c is a vector with elements 0 and 1, with the 1's in positions corresponding to the index set $\hat{\mathcal{A}}$. The dual of (26) is

$$\begin{gathered} \max b_1^T y_1 + b_2^T y_2 \quad \text{subject to} \\ \left[\, A^T \; -A^T \; I \,\right] \begin{bmatrix} y_1 \\ y_2 \\ s \end{bmatrix} = -c, \qquad (y_1, y_2, s) \ge 0. \end{gathered}$$

When the set $\hat{\mathcal{A}}$ is changed, some of the 1's in the vector c are replaced by zeros. When only a few such changes are made, and the previous optimal basis is used to hot-start the method, we expect that only a few iterations of the dual simplex method will be needed to recover the solution of the new linear program.

4. SQP and Stabilized SQP

In the best-known form of the SQP algorithm (with exact second-order information), the following inequality constrained subproblem is solved to obtain the step Δz at each iteration:

$$\begin{aligned} &\min_{\Delta z}\ \Delta z^T \nabla \phi(z) + \tfrac{1}{2} \Delta z^T \mathcal{L}_{zz}(z,\lambda) \Delta z, \\ &\quad \text{subject to } g(z) + \nabla g(z)^T \Delta z \le 0, \end{aligned} \tag{27}$$

where (z,λ) is the current primal-dual iterate. Denoting the Lagrange multipliers for the constraints in (27) by λ^+, we see that the solution Δz satisfies the following KKT conditions (cf. (6)):

$$\begin{bmatrix} \mathcal{L}_{zz}(z,\lambda)\Delta z + \nabla \phi(z) + \nabla g(z) \lambda^+ \\ g(z) + \nabla g(z)^T \Delta z \end{bmatrix} \in \begin{bmatrix} 0 \\ N(\lambda^+) \end{bmatrix}, \tag{28}$$

where $N(\cdot)$ is defined as in (7).

In the stabilized SQP method, we choose a parameter $\mu \ge 0$ and seek a solution of the following minimax subproblem for $(\Delta z, \lambda^+)$ such that $(\Delta z, \lambda^+ - \lambda)$ is small:

$$\begin{aligned} &\min_{\Delta z} \max_{\lambda^+ \ge 0}\ \Delta z^T \nabla \phi(z) + \tfrac{1}{2} \Delta z^T \mathcal{L}_{zz}(z,\lambda) \Delta z \\ &\quad + (\lambda^+)^T [g(z) + \nabla g(z)^T \Delta z] - \tfrac{1}{2}\mu \|\lambda^+ - \lambda\|^2. \end{aligned} \tag{29}$$

The parameter μ can depend on an estimate of the distance $\delta(z,\lambda)$ to the primal-dual solution set; for example, $\mu = \eta(z,\lambda)^\sigma$ for some $\sigma \in (0,1)$. We can also write (29) as a linear complementarity problem, corresponding to (28), as follows:

$$\begin{bmatrix} \mathcal{L}_{zz}(z,\lambda)\Delta z + \nabla \phi(z) + \nabla g(z) \lambda^+ \\ g(z) + \nabla g(z)^T \Delta z - \mu(\lambda^+ - \lambda) \end{bmatrix} \in \begin{bmatrix} 0 \\ N(\lambda^+) \end{bmatrix}. \tag{30}$$

Li and Qi [10] derive a quadratic program in $(\Delta z, \lambda^+)$ that is equivalent to (29) and (30):

$$\begin{aligned} &\min_{(\Delta z,\lambda^+)}\ \Delta z^T \nabla \phi(z) + \tfrac{1}{2} \Delta z^T \mathcal{L}_{zz}(z,\lambda) \Delta z + \tfrac{1}{2}\mu \|\lambda^+\|^2, \\ &\quad \text{subject to } g(z) + \nabla g(z)^T \Delta z - \mu(\lambda^+ - \lambda) \le 0. \end{aligned} \tag{31}$$

Under conditions stronger than those assumed in this paper, the results of Wright [18] and Hager [8] can be used to show that the iterates generated by (29) (or (30) or (31)) yield superlinear convergence of the sequence (z^k, λ^k) of Q-order $1+\sigma$. Our aim in the next section is to add a strategy for adjusting the multiplier, with a view to obtaining superlinear convergence under a weaker set of conditions.

5. Multiplier Adjustment and Superlinear Convergence

We show in this section that through use of Procedure ID0 and the multiplier adjustment strategy (24), we can devise a stabilized SQP algorithm that converges superlinearly whenever the initial iterate (z^0, λ^0) is sufficiently close to the primal-dual solution set $\mathcal{S}$. Only Assumption 1 is needed for this result.

Key to our analysis is Theorem 1 of Hager [8]. We state this result in Appendix A, using our current notation and making a slight correction to the original statement. Here we state an immediate corollary of Hager's result that applies under our standing assumption.

Corollary 1. *Suppose that Assumption 1 holds, and let $\lambda^* \in \mathcal{S}_\lambda$ be such that $\lambda_i^* > 0$ for all $i \in \mathcal{B}_+$. Then for any sufficiently large positive σ_0, there are positive constants ρ_0, σ_1, $\gamma \geq 1$, and $\bar{\beta}$ such that $\sigma_0\rho_0 < \sigma_1$, with the following property: For any (z^0, λ^0) with*

$$\|(z^0, \lambda^0) - (z^*, \lambda^*)\| \leq \rho_0, \tag{32}$$

we can generate an iteration sequence $\{(z^k, \lambda^k)\}$, $k = 0, 1, 2, \ldots$, by setting

$$(z^{k+1}, \lambda^{k+1}) = (z^k + \Delta z, \lambda^+),$$

where, at iteration k, $(\Delta z, \lambda^+)$ is the local solution of the sSQP subproblem with

$$(z, \lambda) = (z^k, \lambda^k), \quad \mu = \mu_k \in [\sigma_0\|z^k - z^*\|, \sigma_1], \tag{33}$$

that satisfies

$$\left\|(z^k + \Delta z, \lambda^+) - (z^*, \lambda^*)\right\| \leq \gamma \left\|(z^0, \lambda^0) - (z^*, \lambda^*)\right\|. \tag{34}$$

Moreover, we have

$$\delta(z^{k+1}, \lambda^{k+1}) \leq \bar{\beta}\left[\delta(z^k\lambda^k)^2 + \mu_k\delta(\lambda^k)\right]. \tag{35}$$

Recalling our definition (9) of ϵ_λ, we define the following parametrized subset of $\mathcal{S}_\lambda$:

$$\mathcal{S}_\lambda^\nu \stackrel{\text{def}}{=} \{\lambda \in \mathcal{S}_\lambda \mid \min_{i \in \mathcal{B}_+} \lambda_i \geq \nu\epsilon_\lambda\}. \tag{36}$$

It follows easily from the MFCQ assumption and (9) that $\mathcal{S}_\lambda^\nu$ is nonempty, closed, bounded, and therefore compact for any $\nu \in [0, 1]$.

We now show that the particular choice of stabilization parameter $\mu = \eta(z, \lambda)^\sigma$, for some $\sigma \in (0, 1)$, eventually satisfies (33).

Lemma 4. *Suppose the assumptions of Corollary 1 are satisfied, and let λ^* be as defined there. Let σ be any constant in $(0, 1)$. Then there is a quantity $\rho_2 \in (0, \rho_0]$ such that when (z^0, λ^0) satisfies*

$$\|(z^0, \lambda^0) - (z^*, \lambda^*)\| \leq \rho_2, \tag{37}$$

the results of Corollary 1 hold when we set the stabilization parameter at iteration k to the following particular value:

$$\mu = \mu_k = \eta(z^k, \lambda^k)^\sigma. \tag{38}$$

Proof. We prove the result by showing that μ_k defined by (38) satisfies (33) for some choice of ρ_2. For contradiction, suppose that no such choice of ρ_2 is possible, so that for each $\ell = 1, 2, 3, \ldots$, there is a starting point $(z^0_{[\ell]}, \lambda^0_{[\ell]})$ with

$$\left\|(z^0_{[\ell]}, \lambda^0_{[\ell]}) - (z^*, \lambda^*)\right\| \leq \ell^{-1}\rho_0 \tag{39}$$

such that the sequence $\left\{\left(z^k_{[\ell]}, \lambda^k_{[\ell]}\right)\right\}_{k=0,1,2,\ldots}$ generated from this starting point in the manner prescribed by Corollary 1 with $\mu_k = \eta(z^k_{[\ell]}, \lambda^k_{[\ell]})^\sigma$ eventually comes across an index k_ℓ such that this choice of μ_k violates (33), that is, one of the following two conditions holds:

$$\sigma_0 \left\|z^{k_\ell}_{[\ell]} - z^*\right\| > \eta(z^k_{[\ell]}, \lambda^k_{[\ell]})^\sigma, \tag{40a}$$

$$\sigma_1 < \eta(z^k_{[\ell]}, \lambda^k_{[\ell]})^\sigma. \tag{40b}$$

Assume that k_ℓ is the first such index for which the violation (40) occurs. By (34) and (39), we have that

$$\left\|\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right) - (z^*, \lambda^*)\right\| \leq \gamma \left\|\left(z^0_{[\ell]}, \lambda^0_{[\ell]}\right) - (z^*, \lambda^*)\right\| \leq \gamma \ell^{-1}\rho_0. \tag{41}$$

Therefore by Theorem 2 and (13), we have for ℓ sufficiently large that

$$\begin{aligned}
\frac{\eta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right)^\sigma}{\left\|z^{k_\ell}_{[\ell]} - z^*\right\|} &\geq \frac{\eta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right)^\sigma}{\delta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right)} \\
&\geq \kappa_0^\sigma \delta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right)^{\sigma-1} \\
&\geq \kappa_0^\sigma \left\|\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right) - (z^*, \lambda^*)\right\|^{\sigma-1} \\
&\geq \kappa_0^\sigma \gamma^{\sigma-1}\rho_0^{\sigma-1}\ell^{1-\sigma}.
\end{aligned} \tag{42}$$

Hence, taking limits as $\ell \uparrow \infty$, we have that

$$\frac{\eta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right)^\sigma}{\left\|z^{k_\ell}_{[\ell]} - z^*\right\|} \to \infty \quad \text{as } \ell \uparrow \infty.$$

Dividing both sides of (40a) by $\left\|z^{k_\ell}_{[\ell]} - z^*\right\|$, we conclude from finiteness of σ_0 that (40a) is impossible.

By using Theorem 2 again together with (41), we obtain

$$\begin{aligned}
\eta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right) &\leq \kappa_1 \delta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right) \\
&\leq \kappa_1 \left\|\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right) - (z^*, \lambda^*)\right\| \\
&\leq \kappa_1 \gamma \rho_0 \ell^{-1},
\end{aligned}$$

and therefore $\eta\left(z^{k_\ell}_{[\ell]}, \lambda^{k_\ell}_{[\ell]}\right)^\sigma \to 0$ as $\ell \uparrow \infty$. Hence, (40b) cannot occur either, and the proof is complete.

We now use a compactness argument to extend Corollary 1 from the single multiplier λ^* in the relative interior of $\mathcal{S}_\lambda$ to the entire set $\mathcal{S}_\lambda^\nu$, for any $\nu \in (0,1]$.

Theorem 6. *Suppose that Assumption 1 holds, and fix $\nu \in (0,1]$. Then there are positive constants $\hat{\delta}$, $\gamma \geq 1$, and β such that the following property holds: Given (z^0, λ^0) with*

$$\mathrm{dist}\left((z^0,\lambda^0), \mathcal{S}_\lambda^\nu\right) \leq \hat{\delta},$$

the iteration sequence $\{(z^k,\lambda^k)\}_{k=0,1,2,\ldots}$ generated in the manner described in Corollary 1, with μ_k, $k = 0,1,2\ldots$ chosen according to (38), satisfies the following relations:

$$\delta(z^{k+1},\lambda^{k+1}) \leq \beta\delta(z^k,\lambda^k)^{1+\sigma} \tag{43a}$$

$$\lambda_i^k \geq \frac{1}{2}\nu\epsilon_\lambda, \quad \textit{for all } i \in \mathcal{B}_+ \textit{ and all } k = 0,1,2\ldots. \tag{43b}$$

Proof. For each $\lambda^* \in \mathcal{S}_\lambda^\nu$, we use Corollary 1 to obtain positive constants $\sigma_0(\lambda^*)$ (sufficiently large), $\sigma_1(\lambda^*)$, $\gamma(\lambda^*)$, and $\bar{\beta}(\lambda^*)$, using the argument λ^* for each constant to emphasize the dependence on the choice of multiplier λ^*. In the same vein, let $\rho_2(\lambda^*) \in (0, \rho_0(\lambda^*)]$ be the constant from Lemma 4. Now choose $\hat{\delta}(\lambda^*) > 0$ for each $\lambda^* \in \mathcal{S}_\lambda^\nu$ in such a way that

$$0 < \hat{\delta}(\lambda^*) \leq \tfrac{1}{2}\rho_2(\lambda^*), \tag{44a}$$

$$\gamma(\lambda^*)\hat{\delta}(\lambda^*) \leq \tfrac{1}{4}\nu\epsilon_\lambda, \tag{44b}$$

and consider the following open cover of $\mathcal{S}_\lambda^\nu$:

$$\cup_{\lambda^* \in \mathcal{S}_\lambda^\nu} \left\{\lambda \,|\, \|\lambda - \lambda^*\| < \hat{\delta}(\lambda^*)\right\}. \tag{45}$$

By compactness of $\mathcal{S}_\lambda^\nu$, we can find a finite subcover defined by points $\hat{\lambda}^1, \hat{\lambda}^2, \ldots, \hat{\lambda}^f \in \mathcal{S}_\lambda^\nu$ as follows:

$$\mathcal{S}_\lambda^\nu \subset \mathcal{V} \stackrel{\mathrm{def}}{=} \cup_{j=1,2,\ldots,f} \left\{\lambda \,|\, \|\lambda - \hat{\lambda}^j\| < \hat{\delta}(\hat{\lambda}^j)\right\}. \tag{46}$$

$\mathcal{V}$ is an open neighborhood of $\mathcal{S}_\lambda^\nu$. Now define

$$\gamma \stackrel{\mathrm{def}}{=} \max_{j=1,2,\ldots,f} \gamma(\hat{\lambda}^j), \quad \bar{\beta} \stackrel{\mathrm{def}}{=} \max_{j=1,2,\ldots,f} \bar{\beta}(\hat{\lambda}^j), \quad \delta \stackrel{\mathrm{def}}{=} \max_{j=1,2,\ldots,f} \hat{\delta}(\hat{\lambda}^j). \tag{47}$$

Also, choose a quantity $\hat{\delta} > 0$ with the following properties:

$$\hat{\delta} \leq \min_{j=1,2,\ldots,f} \hat{\delta}(\hat{\lambda}^j) \leq \delta, \tag{48a}$$

$$\left\{\lambda \,|\, \mathrm{dist}(\lambda, \mathcal{S}_\lambda^\nu) \leq \hat{\delta}\right\} \subset \mathcal{V}, \tag{48b}$$

$$\hat{\delta} \leq \frac{\nu\epsilon_\lambda}{4\gamma}, \tag{48c}$$

$$\hat{\delta} \leq 1. \tag{48d}$$

Now consider (z^0, λ^0) with

$$\left\|(z^0, \lambda^0) - (z^*, \lambda^*)\right\| \le \hat{\delta}, \quad \text{for some } \lambda^* \in \mathcal{S}_\lambda^\nu. \tag{49}$$

We have $\mathrm{dist}(\lambda^0, \mathcal{S}_\lambda^\nu) \le \hat{\delta}$, and so $\lambda^0 \in \mathcal{V}$. It follows that for some $j = 1, 2, \dots, f$, we have

$$\|\lambda^0 - \hat{\lambda}^j\| \le \hat{\delta}(\hat{\lambda}^j). \tag{50}$$

Moreover, since $\|z^0 - z^*\| \le \hat{\delta}$, we have from (48a) that

$$\left\|(z^0, \lambda^0) - (z^*, \hat{\lambda}^j)\right\| \le \hat{\delta} + \hat{\delta}(\hat{\lambda}^j) \le 2\hat{\delta}(\hat{\lambda}^j) \le \rho_2(\hat{\lambda}^j), \tag{51}$$

where the final inequality follows from (44a). Application of Corollary 1 and Lemma 4 now ensures that the stabilized SQP sequence starting at (z^0, λ^0) with $\mu = \mu_k$ chosen according to (38) yields a sequence $\{(z^k \lambda^k)\}_{k=0,1,2,\dots}$ satisfying

$$\begin{aligned}\left\|(z^k, \lambda^k) - (z^*, \hat{\lambda}^j)\right\| &\le \gamma(\hat{\lambda}^j) \left\|(z^0, \lambda^0) - (z^*, \hat{\lambda}^j)\right\| \\ &\le 2\gamma(\hat{\lambda}^j)\hat{\delta}(\hat{\lambda}^j) \le 2\gamma\delta, \end{aligned} \tag{52}$$

where we used (47) to obtain the final inequality.

To prove (43a), we have from Lemma 4, Corollary 1, the bound (14), Theorem 2, the definition (47), and the stabilizing parameter choice (38) that

$$\begin{aligned}\delta(z^{k+1}, \lambda^{k+1}) &\le \bar{\beta}(\hat{\lambda}^j) \left[\delta(z^k, \lambda^k)^2 + \mu_k \delta(\lambda^k)\right] \\ &\le \bar{\beta} \left[\delta(z^k, \lambda^k)^2 + \eta(z^k \lambda^k)^\sigma \delta(z^k, \lambda^k)\right] \quad \text{from (47) and (38)} \\ &\le \bar{\beta} \left[\delta(z^k, \lambda^k)^2 + \kappa_1^\sigma \delta(z^k, \lambda^k)^{1+\sigma}\right] \quad \text{from Theorem 2} \\ &\le \bar{\beta} \left((2\gamma\delta)^{1-\sigma} + \kappa_1^\sigma\right) \delta(z^k, \lambda^k)^{1+\sigma}, \end{aligned}$$

where in the last line we use $\delta(z^k, \lambda^k) \le \mathrm{dist}((z^k, \lambda^k), \mathcal{S}_\lambda^\nu) \le 2\gamma\delta$. Therefore, the result (43a) follows by setting $\beta = \bar{\beta}\left((2\gamma\delta)^{1-\sigma} + \kappa_1^\sigma\right)$.

Finally, we have from (44b) (with $\lambda^* = \hat{\lambda}^j$) and (52) that

$$\mathrm{dist}\left((z^k, \lambda^k), \mathcal{S}_\lambda^\nu\right) \le 2\gamma(\hat{\lambda}^j)\hat{\delta}(\hat{\lambda}^j) \le \frac{1}{2}\nu\epsilon_\lambda.$$

Therefore, we have

$$i \in \mathcal{B}_+ \;\Rightarrow\; \lambda_i^k \ge \min_{\lambda^* \in \mathcal{S}_\lambda^\nu} \lambda_i^* - \frac{1}{2}\nu\epsilon_\lambda \ge \nu\epsilon_\lambda - \frac{1}{2}\nu\epsilon_\lambda = \frac{1}{2}\nu\epsilon_\lambda,$$

verifying (43b) and completing the proof.

We are now ready to state a stabilized SQP algorithm, in which multiplier adjustment steps (consisting of Procedure ID0 followed by solution of (24)) are applied when the convergence does not appear to be rapid enough.

Algorithm sSQPa
given $\sigma \in (0,1)$, τ and $\hat{\tau}$ with $0 < \hat{\tau} < \tau < 1$, tolerance `tol`;
given initial point (z^0, λ^0) with $\lambda^0 \geq 0$;
$k \leftarrow 0$;
calculate $\mathcal{A}(z^0, \lambda^0)$ from (17);
call Procedure ID0 to obtain $\mathcal{A}_+$, $\mathcal{A}_0$; solve (24) to obtain $\hat{\lambda}^0$;
$\lambda^0 \leftarrow \hat{\lambda}^0$;
repeat
  solve (29) with $(z,\lambda) = (z^k, \lambda^k)$ and $\mu = \mu_k = \eta(z^k, \lambda^k)^\sigma$
    to obtain $(\Delta z, \lambda^+)$;
  if $\eta(z^k + \Delta z, \lambda^+) \leq \eta(z^k, \lambda^k)^{1+\sigma/2}$
    $(z^{k+1}, \lambda^{k+1}) \leftarrow (z^k + \Delta z, \lambda^+)$;
    $k \leftarrow k+1$;
  else
    calculate $\mathcal{A}(z^k, \lambda^k)$ from (17);
    call Procedure ID0 to obtain $\mathcal{A}_+$, $\mathcal{A}_0$; solve (24) to obtain $\hat{\lambda}^k$;
    $\lambda^k \leftarrow \hat{\lambda}^k$;
  end (if)
until $\eta(z^k, \lambda^k) <$ `tol`.

The following result shows that when (z^0, λ^0) is close enough to $\mathcal{S}$, the initial call to Procedure ID0 is the only one needed.

Theorem 7. *Suppose that Assumption 1 holds. Then there is a constant $\bar{\delta} > 0$ such that for any (z^0, λ^0) with $\delta(z^0, \lambda^0) \leq \bar{\delta}$, the "if" condition in Algorithm sSQPa is always satisfied, and the sequence $\delta(z^k, \lambda^k)$ converges superlinearly to zero with Q-order $1+\sigma$.*

Proof. Our result follows from Theorems 5 and 6. Choose $\nu = 1/2$ in Theorem 6, and let $\hat{\delta}$, γ, and β be as defined there. Using also δ_3 and β' from Theorem 5 and ϵ_λ defined in (9), we choose $\bar{\delta}$ as follows:

$$\bar{\delta} = \min\left(\delta_3, \hat{\delta}, \left(\frac{\epsilon_\lambda}{2\beta'}\right)^{1/\tau}, \left(\frac{\hat{\delta}}{\beta'}\right)^{1/\tau}, \frac{1}{(2\beta)^{1/\sigma}}, \kappa_0 \left(\frac{\kappa_0}{\beta\kappa_1}\right)^{2/\sigma}\right). \tag{53}$$

Now let (z^0, λ^0) satisfy $\delta(z^0, \lambda^0) \leq \bar{\delta}$, and let $\hat{\lambda}^0$ be calculated from (24). From Theorem 5 and (53), we have that

$$\delta(z^0, \hat{\lambda}^0) \leq \beta' \delta(z^0, \lambda^0)^\tau \leq \beta' \bar{\delta}^\tau \leq \frac{1}{2}\epsilon_\lambda \tag{54}$$

and

$$\hat{\lambda}_i^0 \geq \epsilon_\lambda, \quad \text{for all } i \in \mathcal{B}_+, \tag{55a}$$
$$\hat{\lambda}_i^0 = 0, \quad \text{for all } i \notin \mathcal{B}_+. \tag{55b}$$

Since $\mathcal{S}_\lambda$ is closed, there is a vector $\hat{\lambda}^* \in \mathcal{S}_\lambda$ such that

$$\delta(z^0, \hat{\lambda}^0) = \left\| (z^0, \hat{\lambda}^0) - (z^*, \hat{\lambda}^*) \right\|. \tag{56}$$

From (54) and (55a), we have that

$$i \in \mathcal{B}_+ \;\Rightarrow\; \hat{\lambda}_i^* \geq \hat{\lambda}_i^0 - \frac{1}{2}\epsilon_\lambda \geq \frac{1}{2}\epsilon_\lambda,$$

so that $\hat{\lambda}^* \in \mathcal{S}_\lambda^\nu$ for $\nu = 1/2$. We therefore have from (54), (56), and (53) that

$$\operatorname{dist}((z^0, \hat{\lambda}^0), \mathcal{S}_\lambda^\nu) = \left\| (z^0, \hat{\lambda}^0) - (z^*, \hat{\lambda}^*) \right\| \leq \beta' \bar{\delta}^\tau \leq \hat{\delta}. \tag{57}$$

From here on, we set $\lambda^0 \leftarrow \hat{\lambda}^0$, as in Algorithm sSQPa. Because of the last bound, we can apply Theorem 6 to (z^0, λ^0). We use this result to prove the following claims. First,

$$\bar{\delta} \geq \delta(z^0, \lambda^0) \geq 2\delta(z^1, \lambda^1) \geq 4\delta(z^2, \lambda^2) \geq \cdots. \tag{58}$$

Second,

$$\eta(z^{k+1}, \lambda^{k+1}) \leq \eta(z^k, \lambda^k)^{1+\sigma/2}, \quad \text{for all } k = 0, 1, 2, \ldots. \tag{59}$$

We prove both claims by induction. For $k = 0$ in (58), we have from (57) and $\bar{\delta} \leq \hat{\delta}$ in (53) that $\delta(z^0, \lambda^0) \leq \bar{\delta}$. Assume that the first $k+1$ inequalities in (58) have been verified. From (43a) and (53), we have that

$$\delta(z^{k+1}, \lambda^{k+1}) \leq \beta\delta(z^k, \lambda^k)^{1+\sigma} \leq \beta\bar{\delta}^\sigma \delta(z^k, \lambda^k) \leq \frac{1}{2}\delta(z^k, \lambda^k),$$

so that the next inequality in the chain is also satisfied. For (59), we have from Theorem 2, (43a), and (58) that

$$\begin{aligned}
\eta(z^{k+1}, \lambda^{k+1}) &\leq \kappa_1 \delta(z^{k+1}, \lambda^{k+1}) \\
&\leq \beta\kappa_1 \delta(z^k, \lambda^k)^{1+\sigma} \\
&\leq \beta\kappa_1 \bar{\delta}^{\sigma/2} \delta(z^k, \lambda^k)^{1+\sigma/2} \\
&\leq \beta\kappa_1 \bar{\delta}^{\sigma/2} \kappa_0^{-1-\sigma/2} \eta(z^k, \lambda^k)^{1+\sigma/2} \\
&\leq \eta(z^k, \lambda^k)^{1+\sigma/2},
\end{aligned}$$

where the last bound follows from (53). Hence, (59) is verified, so that the condition in the "if" statement of Algorithm sSQPa is satisfied for all $k = 0, 1, 2, \ldots$. Superlinear convergence with Q-order $1 + \sigma$ follows from (43a).

6. Summary and Possible Extensions

We have presented a technique for identifying the active inequality constraints at a local solution of a nonlinear programming problem, where the standard assumptions—existence of a strictly complementary solution and linear independence of active constraints gradients—are replaced by weaker assumptions. We have embedded this technique in a stabilized SQP algorithm, resulting in a method that converges superlinearly under the weaker assumptions when started at a point sufficiently close to the (primal-dual) optimal set.

The primal-dual algorithm described by Vicente and Wright [14] can also be improved by using the techniques outlined here. In that paper, strict complementarity is assumed along with MFCQ, and superlinear convergence is proved provided both $\delta(z^0, \lambda^0)$ is sufficiently small and $\lambda_i^0 \geq \gamma$, for all $i \in \mathcal{B} = \mathcal{B}_+$ and some $\gamma > 0$. If we apply the active constraint detection procedure (17) and the subproblem (24) to *any* initial point (z^0, λ^0) with $\delta(z^0, \lambda^0)$ sufficiently small, the same convergence result can be obtained without making the positivity assumption on the components of $\lambda^0_{\mathcal{B}_+}$. (Because of the strict complementarity assumption, Procedure ID0 serves only to verify that $\mathcal{B} = \mathcal{B}_+$.)

Numerous issues remain to be investigated. We believe that degeneracy is an important issue, given the large size of many modern applications of nonlinear programming and their nature as discretizations of continuous problems. Nevertheless, the practical usefulness of constraint identification and stabilization techniques remains to be investigated. The numerical implications should also be investigated, since implementation of these techniques may require solution of ill-conditioned systems of linear equations (see M. H. Wright [15] and S. J. Wright [17]). Embedding of these techniques into globally convergence algorithmic frameworks needs to be examined. We should investigate generalization to equality constraints, possibly involving the use of the "weak" MFCQ condition, which does not require linear independence of the equality constraint gradients.

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A. Hager's Theorem

We restate Theorem 1 of Hager [8], making a slight correction to the original statement concerning the conditions on (z^0, λ^0) and the radius of the neighborhood containing the sequence $\{(z^k, \lambda^k)\}$. No modification to Hager's analysis is needed to prove the following version of this result.

Theorem 8. *Suppose that z^* is a local solution of (1), and that ϕ and g are twice Lipschitz continuously differentiable in a neighborhood of z^*. Let λ^* be*

some multiplier such that the KKT conditions (3) are satisfied, and define

$$\bar{\mathcal{B}} \stackrel{\text{def}}{=} \{i \,|\, \lambda_i^* > 0\}.$$

Suppose that there is an $\alpha > 0$ *such that*

$$w^T \mathcal{L}_{zz}(z^*, \lambda^*) w \ge \alpha \|w\|^2, \text{ for all } w \text{ such that } \nabla g_i(z^*)^T w = 0, \text{ for all } i \in \bar{\mathcal{B}}.$$

Then for any choice of σ_0 *sufficiently large, there are positive constants* ρ_0, σ_1, $\gamma \ge 1$, *and* $\bar{\beta}$ *such that* $\sigma_0 \rho_0 < \sigma_1$, *with the following property: For any* (z^0, λ^0) *with*

$$\|(z^0, \lambda^0) - (z^*, \lambda^*)\| \le \rho_0,$$

we can generate an iteration sequence $\{(z^k, \lambda^k)\}$, $k = 0, 1, 2, \ldots$, *by setting*

$$(z^{k+1}, \lambda^{k+1}) = (z^k + \Delta z, \lambda^+),$$

where, at iteration k, $(\Delta z, \lambda^+)$ *is the local solution of the sSQP subproblem with*

$$(z, \lambda) = (z^k, \lambda^k), \qquad \mu = \mu_k \in [\sigma_0 \|z^k - z^*\|, \sigma_1],$$

that satisfies

$$\left\|(z^k + \Delta z, \lambda^+) - (z^*, \lambda^*)\right\| \le \gamma \left\|(z^0, \lambda^0) - (z^*, \lambda^*)\right\|.$$

Moreover, we have

$$\delta(z^{k+1}, \lambda^{k+1}) \le \bar{\beta} \left[\delta(z^k \lambda^k)^2 + \mu_k \delta(\lambda^k)\right].$$

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